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## **Abstract**

This paper presents a bond-slip model for interfaces between near-surface mounted (NSM) CFRP strips and concrete where debonding occurs due to cohesion failure in the concrete adjacent to the CFRP strip. This bond-slip model was derived on the basis of numerical results from a parametric study conducted using a verified 3-D meso-scale finite element (FE) model. In the proposed bond-slip model, the concrete compressive strength and the groove height-to-width ratio are the two main parameters: the former indicates how strong the concrete itself is while the latter represents the level of confinement provided by the surrounding concrete to the bonded interface. The proposed bond-slip model provides an essential building block for an FE model for predicting debonding failures of RC structures strengthened with NSM CFRP strips.

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# Bond-Slip Model for Interfaces between Near-Surface Mounted CFRP Strips and Concrete

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**Keywords:** NSM (Near surface mounted technique); CFRP; Numerical analysis; Debonding.

## SUMMARY

This paper presents a bond-slip model for interfaces between near-surface mounted (NSM) CFRP strips and concrete where debonding occurs due to cohesion failure in the concrete adjacent to the CFRP strip. This bond-slip model was derived on the basis of numerical results from a parametric study conducted using a verified 3-D meso-scale finite element (FE) model. In the proposed bond-slip model, the concrete compressive strength and the groove height-to-width ratio are the two main parameters: the former indicates how strong the concrete itself is while the latter represents the level of confinement provided by the surrounding concrete to the bonded interface. The proposed bond-slip model provides an essential building block for an FE model for predicting debonding failures of RC structures strengthened with NSM CFRP strips.

## 1. INTRODUCTION

Strengthening of reinforced concrete (RC) members with externally bonded fibre-reinforced polymer (FRP) laminates has become a popular technique over the past two decades [e.g. 1, 2]. More recently, the near-surface mounted (NSM) FRP strengthening technique [3] has attracted significant attention worldwide as an effective alternative to the externally bonded FRP strengthening technique. In the NSM FRP strengthening method, grooves are first cut in the cover concrete of RC members (or the surface layer of other structural members); FRP bars together with adhesive are then placed in the grooves to bond the FRP bars to the concrete.

FRP bars used in the NSM strengthening method may have various cross-sectional shapes, including round, square, elliptical and rectangular. In the present study, only FRP strips, as a special form of rectangular bars with a large section height-to-width (thickness) ratio, are considered. FRP strips are a common form of NSM FRP reinforcement due to their advantage over FRP bars of other shapes in bond performance: an FRP strip usually has a much larger perimeter (and hence a much larger area for interfacial bonding) for the same cross-sectional area than an FRP bar of other shapes, which leads to a fuller utilization of the tensile strength of the FRP material [e.g. 4]. FRP strips made of CFRP are particularly attractive as the high strength of CFRP leads to a small cross-sectional area, which is desirable for NSM strengthening applications. The present study is focused on CFRP strips which are defined as CFRP rectangular bars with a sectional height-to-width (thickness) ratio larger than 5. These CFRP strips are typically procured bars with unidirectional fibres oriented in the longitudinal direction; they often have a rough surface texture for enhanced bonding with the adhesive.

A bond-slip model depicts the relationship between the bond shear stress and the relative slip between the two bonded adherends. An accurate bond-slip model for NSM CFRP strip-to-concrete interfaces is of fundamental importance to the accurate modelling and in-depth understanding of debonding failures in concrete structures strengthened with NSM CFRP strips. Several debonding failure modes have been observed in tests of NSM CFRP strip-to-concrete bonded joints. Among these failure modes, the commonest and most desirable mode is debonding due to cohesion failure in the concrete near the epoxy-concrete bi-material interface (i.e. failure within the concrete by cracking in the concrete layer adjacent to the adhesive layer). Existing test results have indicated that cohesion failure-induced debonding can be expected provided that the surfaces of concrete and FRP are properly prepared and the adhesive is appropriately selected [e.g. 5, 6]. Cohesion failure induced debonding is the most desirable debonding mode for two reasons: (a) the benefit of strengthening is maximized as failure occurs in the original structure rather than in the strengthening system; and (2) the development of a design theory is made easier as the properties of concrete rather than the properties of the adhesive or the two bi-material interfaces (i.e. the epoxy-to-concrete interface and the FRP-to-epoxy interface) govern the strength. The properties of a bi-material interface depend on the method and degree of surface treatment which are difficult to control and quantify on site. Weak adhesives should obviously not be used to avoid cohesion failure in the adhesive. Therefore, this paper is concerned only with the development of a bond-slip model for CFRP strips near-surface mounted to concrete with debonding due to cohesion failure in the concrete.

## **2. EXISTING STUDIES**

A number of bond-slip models have been developed for FRP laminates externally bonded to concrete [e.g. 7, 8], but there has been rather limited work on bond-slip models for FRP strips near-surface mounted to concrete. Sena-Cruz and Barros [9] proposed a bond-slip model for NSM CFRP strips in concrete based on a model commonly used for steel bar-to-concrete interfaces [10]. Sena-Cruz and Barros's model [9] was calibrated using the results of their own tests where failure occurred in the concrete-adhesive and adhesive-FRP interfaces. More recently, Borchert and Zilch [11] recommended the use of a bond-slip model adopted by CEB-FIP [12] for modelling NSM CFRP strips in concrete, but this model was also originally proposed for steel bar-to-concrete interfaces. In addition, Seracino et al. [13] recommended the use of a bilinear bond-slip model which has the same form as that for FRP laminates externally bonded to concrete. The validity of these models, however, is still uncertain in the sense that they were not directly deduced from tests or FE simulations of NSM CFRP strip-to-concrete bonded joints. Instead, they are assumed relationships based on previous work on steel bar-to-concrete interfaces or on externally bonded FRP-to-concrete interfaces. Therefore, further research is needed to develop a more reliable bond-slip relationship for CFRP strips near-surface mounted to concrete. The development of such a bond-slip model can be through the direct regression of experimental results (referred to as the experimental approach) or a numerical parametric study (referred to as the numerical approach). The former approach is not easy to realise as the required measurements of strains may interfere with the bond-slip behaviour. In the present study, the numerical simulation approach was adopted: a parametric study was conducted using a 3-D meso-scale FE model previously developed and validated by the authors [14] to generate numerical results for the development of a bond-slip model.

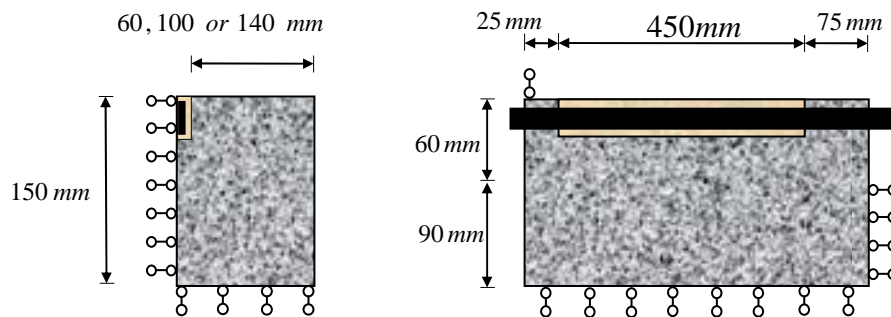
## **3. PARAMETRIC STUDY**

A 3-D meso-scale FE model previously developed and validated by the authors [14] was employed in the parametric study to simulate the single-lap shear test (Figure 1). In the 3-D meso-scale FE model, elements of the order of 1 mm in size are employed. The concrete is simulated using the orthogonal fixed smeared crack model while the FRP and the adhesive are treated as linear brittle-cracking materials. The 3-D meso-scale FE model was calibrated and verified using results of well-documented

bonded joint tests. More details of this 3-D meso-scale FE model are available elsewhere [14]. Some aspects of the FE model are illustrated in Figure 2.



**Figure 1:** Single-lap shear test



**Figure. 2:** NSM FRP strip-to-concrete bonded joint as modelled in the FE parametric study

The bond behaviour of an NSM CFRP strip differs from that of an externally bonded FRP laminate in at least two aspects: (1) the NSM CFRP strip has a much larger area of bonded interface as the FRP strip is surrounded by concrete on three sides; (2) significant confinement to the CFRP strip is provided by the surrounding concrete. While these two features generally lead to a larger bond strength for NSM CFRP strips, they also make the bond behaviour more complicated. The factors that could possibly influence the bond behaviour include the concrete strength  $f_c$ , groove height-to-width  $h_g / w_g$  ratio, properties and dimensions of the NSM CFRP strip, as well as the properties and thickness of the adhesive layer. A preliminary FE study [14] indicated that for NSM CFRP strip-to-concrete bonded joints that are governed by cohesion failure in concrete, the concrete compressive strength and the groove height-to-width ratio are the two key parameters: the former reflects how strong the concrete itself is while the latter represents the level of confinement provided by the surrounding concrete to the bonded interface. Other parameters of the bonded joint were found to have only minor effects on the bond behaviour [14].

Based on the conclusion of the preliminary FE study, in the FE parametric study presented here, only the concrete strength and the groove height-to-width ratio were varied. Three values of the concrete cylinder compressive strength (20 MPa, 30 MPa and 40 MPa) and three groove height-to-width ratios (2.33, 4.00 and 5.67) were considered in the parametric study. The three height-to-width ratios were achieved by using three different groove depths (14 mm, 24 mm and 34 mm) but the same groove width of 6 mm. These grooves were for a 2 mm thick CFRP strip having three different strip heights respectively and located at the mid-width of the groove, with a 2 mm thick adhesive layer on each side. The maximum groove height was limited to 34 mm as in most practical cases the thickness of the concrete cover is not much larger than 35 mm. The minimum groove height of 14 mm was selected to maintain a strip height-to-thickness ratio of 5 (lower limit ratio for CFRP strips). The other parameters of concern were assigned appropriate values in practice: the elastic modulus and Poisson's ratio of the

CFRP strip were taken to be 150 GPa and 0.2 respectively in all cases; the thickness, elastic modulus and Poisson's ratio of adhesive were taken to be 2 mm, 3 GPa and 0.35 respectively.

It should be noted that the bond behaviour of NSM CFRP strip-to-concrete interfaces is also affected by the net distances between the groove and the edges of the concrete member, and the net spacing between adjacent grooves, when these distances are not sufficiently large [15]. In the present study, the effects of these two parameters on the bond behaviour were not investigated to simplify the problem to a more manageable one. Therefore, only bonded joints with a single NSM strip were considered in the parametric study, and the concrete edge distances in all numerical cases were chosen to be sufficiently large based on trial FE analyses. A sufficiently large edge distance refers to an edge distance greater than a minimum edge distance, below which the behaviour of the bonded joint is significantly affected by the edge distance. The effects of edge distance and groove spacing are subjects for the future research.

#### 4. BOND-SLIP MODEL

For a bond-slip model to provide accurate predictions, it needs to have an appropriate shape as well as a correct value for the interfacial fracture energy. Special attention was given to these two important issues in the development of the bond-slip model. The bond-slip curves obtained from the parametric study are shown in Figures 3 and 4, and the values of the interfacial fracture energy obtained from the FE analyses are listed in Table 1. In Table 1, for ease of reference, each numerical case is given a name, which starts with "Case" followed by a two-digit number to represent the concrete strength ( $f_c$ ), then a one-digit number to represent the thickness of the CFRP strip ( $t_f$ ), and a two-digit number to represent the height of the CFRP strip ( $h_f$ ), followed by a three-digit number to represent the elastic modulus of the CFRP strip ( $E_f$ ); the last number represents the edge distance of the concrete block ( $a_e$ ).

Table 1. Results from the FE parametric study

Specimen	$f_c$ (MPa)	$t_f$ (mm)	$h_f$ (mm)	$a_e$ (mm)	$E_f$ (GPa)	$h_g/w_g$	$G_f$ (N/mm)	$\tau_{\max}$ (MPa)
Case-20-2-10-150-60	20	2	10	60	150	2.33	3.63	8.09
Case-20-2-20-150-100	20	2	20	100	150	4.00	4.52	8.74
Case-20-2-30-150-140	20	2	30	140	150	5.67	5.24	9.12
Case-30-2-10-150-60	30	2	10	60	150	2.33	4.74	10.5
Case-30-2-20-150-100	30	2	20	100	150	4.00	6.02	11.4
Case-30-2-30-150-140	30	2	30	140	150	5.67	6.98	11.9
Case-40-2-10-150-60	40	2	10	60	150	2.33	5.54	12.3
Case-40-2-20-150-100	40	2	20	100	150	4.00	6.92	13.4
Case-40-2-30-150-140	40	2	30	140	150	5.67	8.04	14.0

Note: The specimens are named as Case-  $f_c$  -  $t_f$  -  $h_f$  -  $E_f$  -  $a_e$

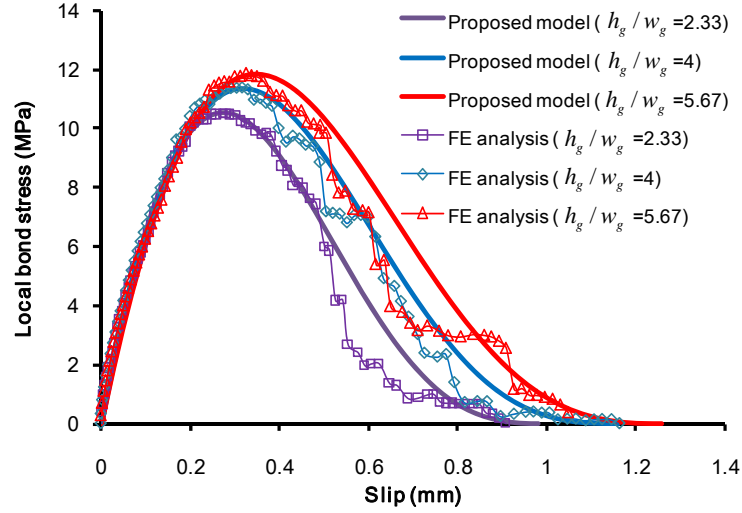
##### 4.1 Shape of bond-slip curves

Figures 3 and 4 indicate that the bond-slip curves of NSM CFRP strip-to-concrete bonded interfaces contain an ascending branch and a descending branch. These figures also indicate that: (1) the slope of the ascending branch decreases continuously until the maximum bond stress is reached; (2) the magnitude of the slope of the descending branch increases first but then decreases with increases of the slip; (3) the ascending branch and the descending branch are basically smoothly connected with no sharp change in slope. The third feature means that it is possible to use a single equation to depict the

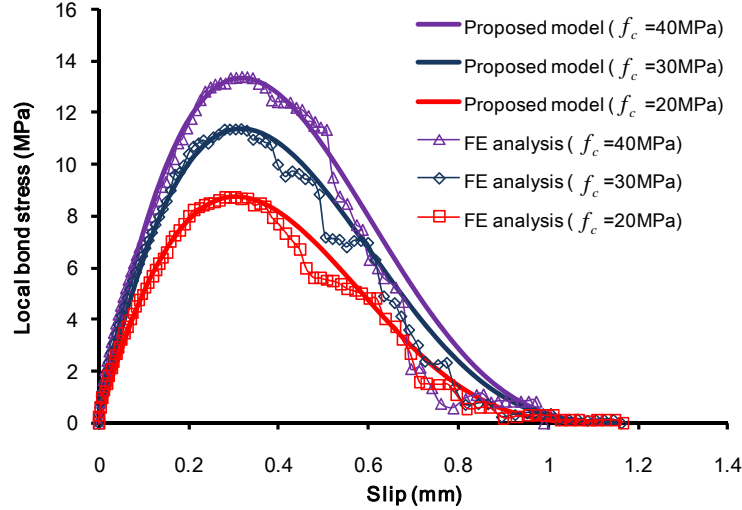
whole bond-slip curve (i.e. containing both the ascending branch and the descending branch), while the first two features suggest that the bond-slip curve may be depicted using the product of a sine function and a power function. Based on the considerations above and sing a trial-and-error process, the bond-slip relationship is proposed to be of the following form:

$$\tau = A\left(\frac{2B-s}{B}\right)^2 \sin\left(\frac{\pi}{2} \cdot \frac{2B-s}{B}\right) \quad \text{with} \quad s \leq 2B \quad (1)$$

where  $\tau$  and  $s$  are the bond stress and the slip respectively;  $A$  and  $B$  are constants to be determined based on results from the parametric study.



**Figure 3:** Bond-slip curves for a concrete strength of 30 MPa



**Figure 4:** Bond-slip curves for a groove height-to-width ratio of 4

#### 4.2 Interfacial fracture energy

Based on the bond-slip curves obtained from the FE parametric study, the interfacial fracture energy was calculated for each of the numerical cases, whose values are listed in Table 1. It is evident that the interfacial fracture energy increases with the concrete strength or the groove height-to-width ratio. By

regression of the results from the parametric study, the following equation is proposed to approximate the interfacial fracture energy:

$$G_f = 0.4\gamma^{0.422}f_c^{0.619} \quad (2)$$

where  $\gamma$  is the groove height-to-width ratio and  $f_c$  is the concrete cylinder compressive strength.

### 4.3 Maximum bond stress

The maximum bond stress obtained from the parametric study is also listed in Table 1 for all the numerical cases. It can be seen from Table 1 that the maximum bond stress also increases with either the concrete strength or the groove height-to-width ratio. By regression of the results from the FE parametric study, the following equation is proposed to approximate the maximum bond stress:

$$\tau_{\max} = 1.15\gamma^{0.138}f_c^{0.613} \quad (3)$$

### 4.4 Constants in the bond-slip model

With Eq. (1), the interfacial fracture energy  $G_f$  can be obtained by integrating the bond stress with respect to the slip, and the maximum bond stress  $\tau_{\max}$  can be obtained with the condition that the derivative of Eq. (1) with respect to the slip is equal to zero. The final expressions of the interfacial fracture energy  $G_f$  and the maximum bond stress  $\tau_{\max}$  in terms of the constants  $A$  and  $B$  are obtained as follows:

$$G_f = 1.514AB \quad (4)$$

$$\tau_{\max} = 1.6A \quad (5)$$

With Eqs. (2), (3), (4) and (5), the constants  $A$  and  $B$  in Eq. (1) can be found as

$$A = 0.72\gamma^{0.138}f_c^{0.613} \quad (6)$$

$$B = 0.37\gamma^{0.284}f_c^{0.006} \quad (7)$$

### 4.5 Accuracy of the proposed bond-slip model

The predictions of the proposed bond-slip model are compared with the FE results in Figure 3 and 4. It is clear that the proposed bond-slip model closely represent the FE results.

## 5. CONCLUDING REMARKS

Using a 3-D meso-scale FE model previously developed and validated by the authors [4], a parametric study was conducted for the development of an accurate bond-slip model for CFRP strips near-surface mounted (NSM) to concrete. The main parameters that govern this bond-slip behaviour were identified to be the concrete strength and the groove height-to-width ratio, so the proposed bond-slip model is expressed as a function of these two parameters. The bond-slip model represents the first ever model of its kind which is specifically developed for NSM CFRP strip-to-concrete bonded interfaces whose behaviour is governed by debonding due to cohesion failure in the concrete near the epoxy-concrete interface. It should be noted that this bond-slip model is applicable only to NSM CFRP strips in



concrete members where both the groove spacing and the edge distances are sufficiently large. Further work is needed to extend the bond-slip model to include the effects of smaller edge distances and groove spacings.

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